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STUDY OF A CONTINENTAL SURFACE ALBEDO ON THE BASIS OF FLIGHT MEASUREMENTS AND STRUCTURE OF THE EARTH'S SURFACE COVER OVER NORTH AMERICA*

ERNEST C. KUNG

Geophysical Fluid Dynamics Laboratory, U.S. Weather Bureau, Washington, D.C.

REID A. BRYSON and DONALD H. LENSCHOW

Department of Meteorology, University of Wisconsin, Madison, Wis.

ABSTRACT

A series of 12 monthly flights along a fixed path in Wisconsin and a series of 4 long-range flights over extensive areas of the United States and Canada were performed during 1963 to measure systematically the surface albedo over various types of the earth's surface, using an instrumented light airplane operating at a low level. An approximate total of 24,000 mi. was flown and roughly 210,000 sets of the measurements were processed for this study. Techniques of measurement and data treatment are discussed.

It is shown, and discussed in detail, that the regional differences and seasonal variations of the surface albedo due to the structure and state of the earth's surface cover are significant. The snow cover is the most important modification of the earth's surface, giving a significantly higher albedo. A quantitative relationship between the increase of surface albedo and snow cover is examined. The surface albedo measured during the flights over typical surface covers over North America, including cities, is presented. The surface covers and their textures over the North American Continent were studied mainly in terms of land use, vegetation type and phenology, soil type, and ground snow cover. The surface albedo values were estimated for various regions of the continent from the flight measurement data, considering the similarity and differences in surface structure among the regions. The resulting seasonal albedo maps of North America are presented and discussed, along with the seasonal variation of the meridional profile of the continental surface albedo.

1. INTRODUCTION

The surface albedo is a measure of the reflectivity of the earth's surface to solar radiation, and is defined as the ratio of the reflected solar energy to the incident solar energy at the earth's surface.

Since the fraction of the incident solar energy which is not reflected at the earth's surface represents the absorbed solar energy available for differential heating of the lower atmosphere, the study of the surface albedo has vital importance in the study of the atmospheric heat budget with its connection to problems of general circulation, air mass modification, and regional climate. It has long been recognized that the horizontal and seasonal variations in the earth's complex surface features should control those of the regional surface albedo, and that the understanding of the overall picture of the surface albedo is an important step in atmospheric research.

Albedo measurements by means of stationary instruments, which constitute most of the reported investigations, may be suitable over certain simple and uniform

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types of terrain, but they are of only limited use in discussions of the albedo of larger and usually more complex surfaces. Measurements by airplanes flying at high altitudes can overcome this difficulty (see, for example, [29]), but extrapolation to the surface level is generally a problem because no firm albedo-height relationship has been established for the range from the surface to high flying altitudes. Indirect determination of the surface albedo from brightness of a photograph obtained by meteorological satellites [5] or airplanes is subject to calibration problems and complex instrumentation. Differences in technique and instrumentation systems used by various investigators cause further hazard in combining their albedo values to study an overall continental surface albedo.

Bauer and Dutton [1, 2] demonstrated the suitability of an instrumented light airplane for surface albedo measurements of this type in their regional study of south-central Wisconsin. In the present study a light, twin-engined plane, equipped with an upward-facing Kipp and Zonen hemispherical solarimeter and a downward-facing parabolic reflector with a Kipp and Zonen solarimeter at the focus, was used for a series of monthly flights over Wisconsin and for long-range flights over North America. Use of an instrumented light airplane permits albedo measurements over areas of large size impossible with stationary instruments, yet from a low level so that height correction of measured albedo values is not necessary.

In nature, any regional area larger than a micrometeorological stationary site is hardly expected to have a simple and uniform surface cover texture. It is rather expected that even within a "uniform" area, micrometeorological parameters, including the surface albedo, should show considerable variability because of the complexity of the components of the surface cover and their complicated response to the environment. In this study the surface albedo values, intensively measured along selected flight paths, are averaged for each section on the paths where relatively "homogeneous" or variously intermingled surface covers are recognized. The averaged surface albedo values will be regarded as the regionally representative values of the sections of the particular geophysical features. The variability of the measured albedo values within a section may be regarded as representative of the heterogeneity of the surface features in the section.

In order to study the regional surface albedo in relation to the surface covers of the North American Continent, flight measurements were performed along a selected path in Wisconsin every month in 1963 and along four long paths over the United States and Canada during 1963 to observe the albedo of different textures of the earth's surface at various times of the year with a single set of instruments. The methods and results of the albedo measurements will be delineated and discussed. In an effort to use the results of the flight measurements in evaluating regional surface albedo, the surface covers and their textures over North America were studied mainly in terms of land use, vegetation type and phenology, soil type, and snow cover. The surface albedo values were estimated for various regions of the continent from the measured albedo data, considering the similarity and differences in surface structure among the regions. The regional albedo values will be presented in the form of continental albedo maps for different seasons, and the significance of horizontal and seasonal variations of the surface albedo will be discussed.

2. INSTRUMENTATION

The airplane used for the measurements in this study was a Cessna 310, a twin-engined four-place airplane with a cruising speed of 180 m.p.h. and a range of approximately 800 mi. Extensive modifications for meteorological measurements have resulted in a less streamlined airplane that is near the maximum allowable gross weight (with a full fuel load, a pilot, and an observer), and that has a reduced cruising speed of about 165 m.p.h.

An instrument housing, about 1.0 m. long, 0.4 m. wide, and 0.25 m. thick, is mounted on the bottom of the airplane to provide a horizontal protected surface for downward-sensing instruments. A downward-facing parabolic reflector, with a Kipp and Zonen solarimeter mounted at the focus, is contained in this housing and measures the upward stream of the reflected short-wave radiation. With the landing gear retracted, the reflector has an unobstructed view of the ground. The effective beam width of the reflector is about 4°, so that at 300 m. above the ground, the solarimeter measures radiation from a circle on the ground of roughly 21 m. diameter.

An upward-facing Kipp and Zonen solarimeter is mounted on the top of the airplane, midway down the fuselage, to measure the downward stream of solar radiation. Essentially, the only obstruction to a 2π-steradian upward view is the lateral cross-section of the vertical stabilizer. If the radiation field sensed by the top solarimeter is assumed to be homogeneous and isotropic, the amount of radiation contributed by the area of the vertical stabilizer is less than 0.6 percent. The only time, therefore, that the effect of this obstruction is not negligible is when the stabilizer casts a shadow on the solarimeter. This can happen only if the sun is less than 37° above the horizon. This situation occurred on several midwinter flights, but only for a few seconds at a time.

The Kipp and Zonen solarimeter gives an output proportional to the incoming solar radiation of about 8 mv. ly.$^{-1}$ min. with an internal resistance of about 10 ohms. The absolute long-term calibration, according to Bener [3], is accurate to an error of less than 4 percent and the time constant is about 2.0 sec. The greater ruggedness and faster response of the Kipp and Zonen solarimeter as compared to, for example, the Eppley pyrheliometer, makes it a more desirable instrument for measurements from an airplane, though it is apparent that an even faster instrument would be desirable for measuring albedo variability as a function of position. The output of the solarimeters is recorded on a Honeywell 906B Visicorder Oscillograph in the form of a trace on light-sensitive paper that is fed through the recorder at 0.2 in./sec.

Since the bottom radiometer does not measure the upward reflected radiation directly over 2π steradians, the measured albedo is not a hemispheric albedo, but a beam albedo of the area intercepted by the 4° effective beam width of the downward-facing parabolic reflector used in the measurements. By using this beam albedo measuring system it is possible to observe the surface albedo down to the scale of the albedo variation from one small area of a surface structure to another. The effect of the reflector is to reduce the effective beam width to 4°, but increase the amount of radiation per solid angle on the solarimeter. It is possible, however, to relate this beam albedo to the hemispherical albedo by comparing the two.

Bauer and Dutton [2] and Dutton [9] assumed that a fresh layer of snow on the ice of a lake was a homogeneous and isotropic surface, and measured the hemispherical and beam albedo values over such a surface. Since the beam albedo must agree with the hemispherical albedo over a homogeneous and isotropic surface, they found the value 1.294 to be a calibration factor for the beam reflector to incorporate all deviations from the ideal parabolic reflector; i.e., hemispherical albedo = true beam albedo = (1.294 × measured albedo over a homogeneous and isotropic surface). They further showed that the ratio of hemispherical albedo to (1.294 × measured beam albedo) was very close to unity for various types of terrain without snow cover, except water. Although this agreement between the hemispherical and beam albedo over various surfaces does not necessarily imply isotropic and homogeneous radiation, except in the cases of uniform snow cover (see [2]), this provides a way to convert the measured beam albedo to the hemispherical albedo. In this study, the same reflector used by Bauer and Dutton was used, and the calibration factor 1.294 was applied to all the measurements.

A further advantage of the beam reflector is the considerable reduction of the errors in albedo measurement which result from horizon light and internal reflections (see section 4 and [19]); this is important since the hemispherical measuring system suffers seriously from errors of this nature at lower sun angles.

3. FLIGHT PROGRAM

To study the basic features of the surface albedo variation in relation to the type of surface cover and the march of seasons, it is desirable to observe the surface albedo in a rather intensive manner along a fixed route. A regular flight path in Wisconsin, which included as many various surface types as possible of a middle latitude zone, was selected for monthly observations. The entire flight path was divided into 51 sections. These were numbered from 0 to 50. Special attention was paid to dividing the flight path in such a way that a uniform surface cover or a texture of typically mixed surface covers could be recognized along a section. The Wisconsin flight path and sectional divisions are shown in figure 1. General features of the surface covers and soil types of these 51 sections are listed in table 1. Detailed information and further subdivisions were considered in albedo mapping, but their descriptions are not contained in table 1. For these, reference may be made to maps and publications of Curtis [7], Hole and Beatty [17], Stone and Thorne [35], Wisconsin Conservation Department [43], Wisconsin Crop and Livestock Reporting Service [44], and Wisconsin State Department of Public Instruction et al. [45].

TABLE 1.—*Principal surface covers and soil types along the selected flight path over Wisconsin*

Section	Surface cover (land use type and forest type)	Soil type
0, 1	Highly productive agricultural land. 10% *	Black silt loams.
2, 3	Highly productive agricultural land. 10%	Greyish-brown silt loams.
4	Woody agricultural land. 15–39%	Greyish-brown silt loams.
5, 6	Woody agricultural land. 20–39%. Lowland hardwoods.	Sands.
7	Woody agricultural land. 20–39%. Lowland hardwoods.	Peat.
8, 9	Woody agricultural land. 20–39%. Oak-hickory.	Sands.
10	Productive agricultural land and forest. 15–59%. Oak-hickory-pines-aspen-northern hardwoods.	Sands and peat.
11	Woody agricultural and land forest. 15–59%. Pines-oak.	Sands.
12	Forest. 40–59% Oak-hickory	Sands.
13, 14	Forest. 40–59%. Northern hardwoods-aspen-oak.	Peat and sands.
15	Forest. 40–59%. Pines	Sands.
16	Productive agricultural land and forest. 15–39%. Aspen-northern hardwoods-spruce.	Sandy loams.
17, 18, 19, 20	Productive agricultural land. 15%	Greyish-yellow silt loams.
21	Woody agricultural land. 40–50%. Northern hardwood.	Greyish-yellow silt loams.
22	Woody agricultural land and forest. 40–59%. Northern hardwood-aspen-pines.	Greyish-yellow and greyish loams.
23	Forest. 40–79%. Aspen-birch-northern hardwoods.	Greyish loams.
24, 25	Forest. 60–79%. Aspen-northern hardwoods	Greyish-yellow silt loams.
26	Forest. 60–85%. Aspen-birch-swamp conifers-pines.	Peat and muck.
27	Forest. 80%. Aspen-birch-pines	Greyish loams.
28	Forest. 80%. Swamp conifers-northern hardwoods.	Greyish loams.
29	Forest. 60–79%. Northern hardwoods	Greyish loams, and sands.
30	Forest. 60–79%. Aspen-birch	Greyish loams, and sands.
31	Productive agricultural land. 15%	Sands and greyish-yellow silt loams.
32	Woody agricultural land. 15–50%. Northern hardwoods.	Greyish loams.
33	Forest. 40–59%. Northern hardwoods	Greyish loams.
34	Forest. 40–59%. Pines	Greyish loams, and sands.
35	Productive and woody agricultural lands. 15–59%. Oak-hickory.	Sands.
36, 37	Productive and woody agricultural lands. 15–50%. Oak-hickory-northern hardwoods.	Greyish-brown silt loams.
38	Productive agricultural land. 19%	Redish clay silt loams and greyish loams.
39	Productive agricultural land near Green Bay suburbs. 15%.	Redish clay loams.
40, 41, 42, 43	Productive agricultural land. 15%	Redish clay loams.
44, 45, 46, 47, 48	Highly productive agricultural land. 15%	Greyish-brown and black silt loams.
49	East-side suburb of Madison	Greyish-brown and black silt loams.
50	Downtown Madison	

*Indicates percentage of land area forested.

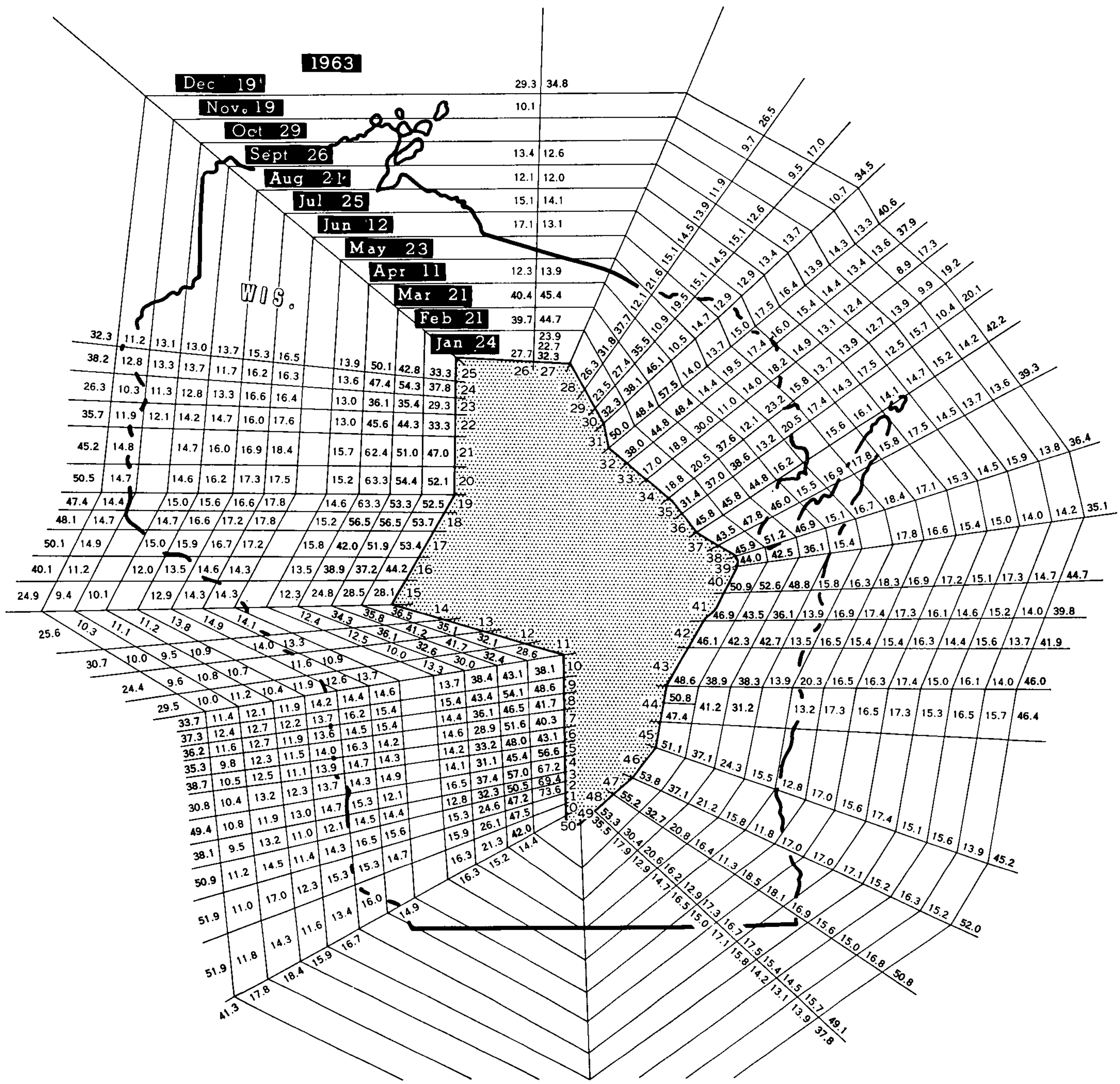

FIGURE 1.—Flight path over Wisconsin and measured surface albedo of the monthly flights.

Usually, under the categories of highly productive agricultural land and productive agricultural land, less than 15 percent of the area is occupied by trees. Under the category of woody agricultural land, 15 percent to 50 percent of the area is occupied by trees. As indicated in table 1, major forest types of Wisconsin include white-red-jack pines, swamp conifers (spruce and fir), oak, hickory, lowland hardwoods (elm, ash, and cottonwood), northern hardwoods (maple and birch), and aspen.

The series of 12 monthly flights over the selected Wisconsin flight path was begun in January 1963 and ended in December 1963. The airplane flew clockwise

TABLE 2.—*Dates and local times of 12 monthly flights, January–December 1963*

Date (1963)	Middleton-Rhinelander	Rhinelander-Middleton
January 24	11:30–13:15	13:45–15:15
February 21	11:25–13:18	14:50–16:10
March 21	10:20–12:00	13:00–14:30
April 11	10:35–12:12	13:20–14:45
May 23	10:10–12:07	13:33–15:00
June 12	11:00–12:40	13:47–15:00
July 25	11:25–13:05	13:53–15:15
August 21	11:00–12:33	13:20–14:48
September 26	9:38–11:13	12:19–13:43
October 29	10:00–11:35	12:37–14:00
November 19	9:48–11:24	12:24–13:46
December 19	11:25–13:10	14:00–15:20

along the path, starting and ending at Morey Airport, Middleton, Wis., with a landing at Rhinelander, Wis., between sections 26 and 27, for refueling. The dates and local times of the flights are listed in table 2.

In an attempt to take as many measurements as possible of surface albedo over various regions of North America, four long-range flight observations were performed over the United States and Canada on the following dates in 1963: March 17; April 14–17; June 28–July 3; September 5–10. The flight paths are shown in figure 4. All four flights started and terminated at Morey Airport, Middleton, Wis., with necessary stops during the flights. All four paths were flown in the counterclockwise direction. The March 17 flight mainly covered the Corn Belt. The April 14–17 flight covered the central United States, including the Corn Belt, midwestern and southern type croplands, pasturelands, open woodlands, and eastern forests. The June 28–July 3 flight covered the northern United States and south-central Canada, including northern type forests, farmlands, pasturelands, grasslands, and woodlands. The September 5–10 flight covered extensive areas in the north-central, southwestern, southern, southeastern, and eastern United States, including various types of deserts, shrubland, and marshland in addition to surface types mentioned above for the other three flights. The four flight paths were subdivided into a total of 1,111 sections in accordance with the texture of the surface covers and the convenience of the data treatment. General features of surface covers along these flight paths may be obtained by comparing figures 4 and 5.

The monthly Wisconsin and four long-range flights totaled approximately 24,000 mi.

4. TECHNIQUE OF MEASUREMENTS

The Wisconsin monthly flights were scheduled so that the measurements were taken as close as possible to local noon in order to reduce errors from low sun angles. In flying the long-range paths, measurements were taken during two to four hours before and after the local noon hour. The measurements taken during the hours of relatively low sun angles (usually before 10 a.m. and after 3 p.m. local time) were carefully checked against the measurements taken over similar surfaces during hours of higher sun angles to eliminate erroneous measurements.

It has been recognized (see Bauer and Dutton [1], and Kuhn and Suomi [19]) that the surface albedo, especially the albedo obtained by the hemispherical system, rapidly increases while the incident solar radiation diminishes when the sun angle becomes quite small. Kuhn and Suomi [19] showed that from 6 a.m. to 6 p.m. in the summer at O'Neill, Nebr., use of a beam reflector could virtually eliminate this apparent increase in albedo caused by the horizon light and internal reflections sensed by an inverted Eppley at low sun angles. The flight investigation of Bauer and Dutton [1] in Wisconsin indicates

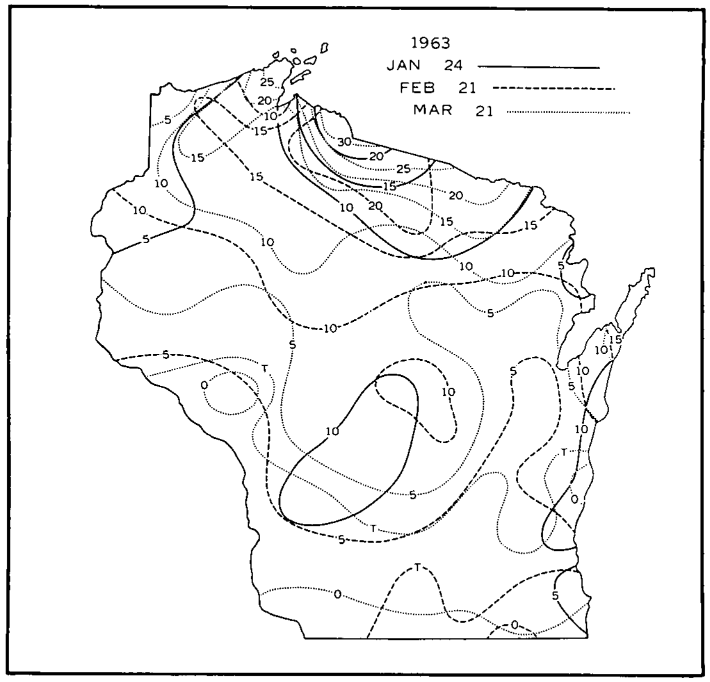

FIGURE 2.—Depth of ground snow cover, in inches, for the flight dates over Wisconsin.

that on April 21, 1960, the albedo values measured both by the beam system and the hemispherical system showed no effect from the sun angle at least between 10:23 and 13:59 local time. According to Bener [3], the Kipp and Zonen solarimeter has an accuracy within an error of 3 percent for global radiation measurements at sun angles of less than 75°. Some of the winter measurements of the Wisconsin flights, and morning and afternoon measurements of the long-range flights were, of necessity, at sun angles less than 60°, but only a small amount of the data was eliminated for obvious errors resulting from low sun angles.

During the flights, an altitude of 300 m. above the ground and a cruising speed of 165 m.p.h. was kept as constant as possible. Kuhn and Suomi [19] found an average change of beam albedo with height of about 1 percent per 1200 m. Bauer and Dutton [2] reported that the albedo measurements made at altitudes up to 300 m. were within the error tolerance of the instruments. Since all the albedo measurements in this study were at altitudes of about 300 m., except in extremely mountainous areas, the height effect is assumed to be negligible.

The cloudy sky, especially the partly cloudy sky, can produce erroneous albedo measurements. For example, one of the solarimeters may be measuring in the direct sun light while the other may be measuring under a cloud shadow. Also, the radiation on the top solarimeter significantly increases when the sun is close to the edge of a cloud. When these cloud edge effects are not present, however, the albedo values measured under cloudy conditions seem to be comparable with those taken under clear sky conditions. Bauer and Dutton [1, 2] used albedo values taken under various sky conditions, from clear to overcast, to show seasonal and regional albedo variations without seeming difficulties.

In this study, an effort was made to take measurements on days when the sky was relatively free of clouds, through it was impossible completely to avoid clouds. The data affected by cloud edges, thick clouds, and clouds near the airplane were carefully eliminated by inspecting the fluctuations of the trace on the recording strip with reference to the flight records. The data taken under scattered clouds were checked carefully whenever possible against the data over similar surface structures taken under clear sky conditions. Special care was taken in reading the recording strip to eliminate the effects of other disturbing factors: records taken when the airplane was not in straight and level flight, when the vertical stabilizer cast a shadow on the top-facing solarimeter, when the instruments did not function properly, or when other possible sources of error appeared on the recording.

Simultaneous outputs of top and ground-facing solarimeters were recorded continuously on the visicorder oscillograph during the measurements over the whole flight path. The positions of the airplane during the flight were manually recorded. Continuous traces on the light-sensitive paper of recordings from both solarimeters were evaluated for the same instants of sensor time. The traces were read every second on the recording strips for the monthly Wisconsin flights and the March 17 long-range flight, corresponding to a spacing of about 0.07 km. This is an adequate interval for the data evaluation of this study, and is almost the densest interval possible to obtain meaningful readings in accordance with the response time of the Kipp and Zonen solarimeter. For the other three long-range flights the traces were read every 3 sec. of the flight, an interval of about 0.22 km. After all seemingly disturbing parts of the recorded data had been eliminated, approximately 210,000 sets of simultaneous readings from both solarimeters were prepared in digital form by a semi-automatic card-punching system. By means of suitable calibration factors, the surface albedo values of all sets of readings, and consequently the mean regional surface albedo value, the standard deviation of the surface albedo, and a coefficient of variability of the albedo (i.e., ratio of standard deviation to mean: see Steel and Torrie [33]) were computed for each section on the flight paths. The albedo and coefficient of variability are both expressed in percent.

5. REGIONAL CONTRAST AND MONTHLY CHANGE OF SURFACE ALBEDO IN WISCONSIN

The computed mean surface albedo values for each section of the Wisconsin flight path, which hereafter will be referred to as the surface albedo of the section, of the monthly observations from January 1963 through December 1963 are presented in figure 1. May, August, and October albedo values may contain some effects of clouds, since the measurements were taken under broken sky conditions; the measurements of the other months were taken under clear or nearly clear conditions. In figure 2, an important modification factor of the surface structure, the depth of the ground snow cover on the flight dates of January, February, and March, is also mapped over the State of Wisconsin. Climatological data of the U.S. Weather Bureau [40] were used in plotting the snow depth.

Persistent deep snow cover on the ground over most of Wisconsin was the characteristic surface feature during January and February. The snow cover still existed over most of the area in March. The ground was again covered by snow during the December flight. To avoid extremely fresh snow cover, the flight measurements were conducted two or three days after a snowfall, so that the snow cover might represent moderate "freshness" between snowfalls. The snow depth on figure 2 shows the snow cover on the flight dates; however, it well expresses the general features of the persistent snow cover pattern from late winter to early spring in March. Snow depth on the December flight date is not presented in figure 2; the pattern was similar to that of January but with somewhat less snow accumulation than in January. (See U.S. Weather Bureau [40]).

The regional albedo values during the winter months are dependent mainly on two factors, snow albedo and the darkness of the nearly black bodies (i.e., trees and buildings, etc.). Figures 1 and 2 show that the surface albedo in deeply snow-covered productive farmlands, where it ranges from 50 to 70, is considerably higher than that in major forest areas, where it ranges from 20 to 50. The snow-covered woody agricultural lands show intermediate albedo values ranging from 35 to 55. The species and dimensions of forest trees, and the reflective properties of snow are decisive factors in determining the albedo of the snow-covered forest areas. For example, the following albedo values were observed in deeply snow-covered dense forests of various tree species: oak 32–42; pine 19–37; aspen and birch 38–50; northern hardwood 19–36; swamp conifer 25–38.

When the ground snow cover is rather shallow, i.e., the snow depth is less than about 5 in., the value of surface albedo is apparently related to the depth of snow and in turn probably to the area of patches covered by the snow, though further accumulation of snow does not seem obviously to increase the albedo. As can be seen in figures 1 and 2, in southern Wisconsin the surface albedo measured in March decreases significantly southward as the depth of snow decreases. This north-south contrast is a very significant feature of the surface albedo in the early spring.

Albedo values observed in Wisconsin during the snow-free season range roughly from 9 to 18. Figure 1 indicates, however, that, in general, the surface albedo values observed in April are lower than those observed in June through July. The surface albedo, therefore, appears to

TABLE 3.—*Surface albedo and coefficient of variability of selected sections of Wisconsin flight path*

Section	Surface Characteristics*	Surface Albedo and (Coefficient of variability**)								
		Jan. 24	Feb. 21	Mar. 21	Apr. 11	June 12	July 25	Sept. 26	Nov. 19	Dec. 19
3	Productive farm land	69.4(57)	50.5(17)	32.3(22)	12.8(27)	14.4(7)	14.5(23)	10.9(15)	9.5(23)	38.1(30)
9	Woody farm land	48.6(21)	54.1(23)	43.4(12)	15.4(10)	15.4(10)	16.2(27)	12.1(11)	12.4(10)	37.3(21)
11	Woody farm land	28.6(26)	32.4(30)	30.0(23)	13.3(11)	13.7(11)	12.6(31)	10.3(10)	10.0(12)	29.5(35)
18	Productive farm land	53.7(17)	56.5(18)	56.5(30)	15.2(11)	17.8(6)	17.2(14)	14.6(7)	14.7(13)	48.1(19)
25	Aspen-northern hardwoods	33.3(33)	42.8(27)	50.1(22)	13.9(18)	16.5(7)	15.3(17)	13.0(14)	11.2(21)	32.3(40)
26	Aspen-birch-swamp-conifers-pines	27.7(31)	39.7(30)	40.4(21)	12.3(23)	17.1(13)	15.1(17)	13.3(11)	10.1(15)	29.3(34)
29	Northern hardwoods	23.5(35)	27.4(51)	35.5(44)	10.9(25)	15.1(35)	14.5(10)	12.6(17)	9.5(11)	17.0(24)
30	Aspen-birch	32.3(20)	38.1(26)	46.1(26)	10.5(30)	12.9(58)	12.9(15)	13.7(13)	10.7(19)	34.5(30)
31	Productive farm land	50.0(19)	48.4(22)	57.5(15)	14.0(16)	15.0(41)	17.5(20)	13.9(13)	13.3(16)	40.6(27)
33	Northern hardwoods	17.0(45)	18.9(70)	30.0(75)	11.0(17)	18.2(18)	14.9(15)	12.3(13)	8.9(11)	17.3(31)
34	Pines	18.8(25)	20.5(67)	37.6(37)	12.1(26)	15.8(22)	13.7(16)	12.7(13)	9.9(21)	19.2(61)
39	Farm land near Green Bay	44.0(30)	42.5(31)	36.1(22)	15.4(9)	17.8(23)	16.6(11)	14.9(7)	14.2(9)	35.1(27)
40	Productive farm land	50.9(16)	52.6(7)	48.8(14)	15.8(10)	18.3(18)	16.9(6)	15.1(6)	14.7(11)	44.7(11)
45	Productive farm land	51.1(10)	37.1(15)	24.3(69)	15.5(26)	17.0(10)	15.6(20)	15.0(8)	13.9(14)	45.2(11)
49	Madison suburb	35.5(34)	17.9(45)	12.9(42)	14.7(14)	15.0(18)	17.1(15)	14.1(17)	13.9(18)	37.8(32)
50	Madison downtown	---	14.4(15)	15.2(17)	16.3(19)	---	---	15.9(11)	17.8(21)	41.3(27)

*See Table 1.
**Coefficient of variability shown in ( ) is percent ratio of standard deviation to the mean albedo in the section.

be related to the phenological cycle of the vegetation. Luxuriant tree leaves and lower vegetation tend to reflect a greater fraction of incident solar energy (though actually absorbed solar energy may be higher because of stronger incident sunlight) than do fewer tree leaves or less dense lower vegetation. This type of observation may provide a quantitative approach to large-scale bioclimatology or phenology.

Probably another factor influencing the surface albedo is the soil moisture content. According to Angstrom's explanation (see Geiger [15]), when the soil particles and plant surface are covered with a film of water, incident rays can enter the water film in all directions, but only rays which can reach the surface of the water film within the limiting angle of total reflection can emerge. In Wisconsin during April the soil moisture content is usually at or near the field capacity as a result of water supplied by melted snow. This may contribute partially to low albedo values observed in April, but this cannot explain the low values in the fall. It is possible that the effect of soil moisture on the surface albedo is hindered by the phenological cycle of vegetation covers.

Soil types can affect the surface albedo directly through soil color and water holding capacity and indirectly through their vegetation cover, so that it is natural to consider soil types in discussing regional surface albedos. It was felt that the region of black silt loam (for example section 48 of the flight paths) tends to show somewhat lower surface albedo than adjacent farmlands during the snow-free season, but the difference is too small to be conclusive. It may be stated that the surface albedo difference due to soil types is less important than that due to vegetation covers, at least where bare soils are not common.

Sixteen sections representing typical surface types along the Wisconsin flight path were arbitrarily selected. Table 3 contains the monthly surface albedo and coefficient of variability of these sections. May, August, and October data are not included for comparison because of the possible effects of clouds during the flights. Listed albedo values in table 3 may concisely illustrate the preceding discussion.

Table 4 illustrates the seasonal change of surface albedo for these 16 sections. The table shows the ratio of surface albedo of a monthly observation to surface albedo of the April observation in each section of the flight path. By such a ratio, the march of the seasons may be traced. Except for section 50, downtown Madison, the very high albedo value suddenly drops after snow melts in the spring, rises somewhat during the early and midsummer, falls again to its lowest value during the fall, and then rises again to the high winter values, thus completing one annual cycle. The increase of the albedo in summer is relatively small in comparison with that in winter, so we recognize two major seasonal variations of the surface albedo: snow-covered and snow-free. In general, it also may be recognized that the albedo increase in winter is much more pronounced in areas where lower vegetation is dominant, such as farmlands, although the actual albedo value of forests is lower than that of farmlands both in winter and summer.

TABLE 4.—*Seasonal variation of surface albedo in Wisconsin as illustrated by ratio of monthly observed albedo to that of April*

Section*	Ratio of monthly observed surface albedo to that of April								
	Jan. 24	Feb. 21	Mar. 21	Apr. 11	June 12	July 25	Sept. 26	Nov. 19	Dec. 19
3	5.42	3.95	2.52	1.00	1.13	1.13	0.85	0.74	2.98
9	3.16	3.51	2.82	1.00	1.00	1.05	0.79	0.81	2.42
11	2.15	2.44	2.26	1.00	1.03	0.95	0.77	0.75	2.22
18	3.53	3.72	3.72	1.00	1.17	1.13	0.96	0.97	3.16
25	2.40	3.08	3.60	1.00	1.19	1.10	0.94	0.81	2.32
26	2.25	3.23	3.28	1.00	1.39	1.23	1.08	0.82	2.38
29	2.16	2.51	3.26	1.00	1.39	1.33	1.16	0.87	1.55
30	3.08	3.63	4.39	1.00	1.23	1.23	1.30	1.02	3.29
31	3.57	3.46	4.11	1.00	1.07	0.89	0.99	0.95	2.90
33	1.55	1.72	2.73	1.00	1.65	1.35	1.12	0.81	1.57
34	1.55	1.69	3.11	1.00	1.31	1.13	1.05	0.82	1.59
39	2.86	2.76	2.34	1.00	1.16	1.08	0.97	0.92	2.28
40	3.22	3.33	3.09	1.00	1.16	1.07	0.96	0.93	2.83
45	3.30	2.39	1.57	1.00	1.10	1.01	0.97	0.90	2.92
49	2.41	1.22	0.88	1.00	1.02	1.16	0.96	0.95	2.57
50	---	0.88	0.93	1.00	---	---	0.98	1.09	2.53

*See Table 1 and 2 for surface characteristics.

TABLE 5.—*Sample analysis of variance of surface albedo data of Wisconsin monthly flight measurements*

Source of variation	Degree of freedom	Sum of squares	Mean square	F
Snow-covered season (Jan., Feb., Mar., and Dec., 1963)				
Section	14	6046.03	431.86	*6.39
Month	3	287.87	95.96	1.42
Error	42	2839.54	67.61	
Total	59	9173.44		
Snow-free season (Apr., June, July, Sept., and Nov., 1963)				
Section	14	147.96	10.57	*8.88
Month	4	173.58	43.40	*36.47
Error	56	66.74	1.19	
Total	74	388.28		

*Extremely significant at 0.5 percent level.

One of the basic approaches in this study is, as discussed in sections 1, 3, and 4, to assume that the averaged surface albedo value in a section of the flight path is the regionally representative surface albedo in that section of the particular surface texture. In this way, the averaged surface albedo in each section may be regarded as an observational value, and its regional and monthly variations may be tested for their statistical significance. The method of analysis of variance for multiway classification (see Steel and Torrie [33]) was applied to the surface albedo values presented in table 3. January, February, March, and December data, and April, June, July, September, and November data were separately grouped and analyzed as albedoes in the snow-covered and snow-free seasons, respectively. Data of section 50 of the flight path were not included in analysis because of missing data in some months. Total variances of the two groups were separately partitioned into three sources of variation: section, month, and error. The results of the analysis of variance, presented in table 5, indicate the following facts:

1. F-value for testing the null hypothesis is extremely significant for the section of the flight path during both snow-covered and snow-free seasons, and for the month during the snow-free seasons. The F-values are not only significant at the usually adopted 1 percent level but also extremely significant at the 0.5 percent level. This is strong evidence that there are real differences of the surface albedo among sections of the flight path, and that there are real monthly variations of surface albedo during the snow-free season although the variations themselves are small.

2. During the snow-covered season the monthly variation of the surface albedo in not statistically significant. The difference of monthly albedo values in each section during this season appears to be due to some factor other than a systematic monthly change, probably the state of the snow cover.

3. Though the coefficient of variabliity (see table 3) within sections of the flight paths is rather large, the averaged value of the surface albedo for a section is representative of the section and can be treated as a single observation value for an area section. This supports our basic concept: to view the regional surface albedo as a synthetic reflectivity of the earth's surface within a given area.

A noteworthy fact in table 3, as discussed in the preceding paragraph, is the rather high coefficients of variability of the surface albedo especially during the snow-covered season. A variability larger than 30 percent is not uncommon and it may reach 70 percent. The flight observations of January, February, March, and December were made on clear-sky days when a cP air mass was present over Wisconsin, so that the top-facing solarimeter output is almost constant. The trace of the ground-facing solarimeter output shows large fluctuations in the amount of reflected solar radiation which occurred during the flight at intervals mainly ranging from 80 m. to 800 m. and were imposed upon the general trend of change of the reflected radiation. These short-interval fluctuations of the reflected radiation are primarily due to the spacing of woodlots, variability of the forest density, mixing of different tree species, and changes in the reflectivity of the snow cover.

The coefficients of variability of the surface albedo in the snow-free months are smaller than those in snow-covered or snow-melting months, varying from less than 10 percent to 30 percent. These coefficients also may express variability in the surface cover within the section, i.e., mixing of different vegetations, buildings, ecological variation of different types of vegetation, soil moisture, etc. Nevertheless special care must be taken when discussing the summer month values of the coefficients. In contrast to the winter month observations, the observations after snow-melting were not completely free of cloud effects, because of the existence of some "summer-type" clouds. The parts of the record, however, which were obviously cloud-affected were eliminated.

Before employment of the instrumented airplane, stationary instrument complexes could not detect this type of variability, which is a parameter that expresses the effect on the reflectivity of the heterogeneity of the texture of the earth's surface cover.

6. SURFACE ALBEDO AND SNOW COVER

As the systematic monthly variation of the surface albedo is not statistically significant, the rather large monthly fluctuation of the surface albedo value during the snow-covered season should be a function of the properties of the snow cover. A synoptic or climatological parameter to indicate extent of the snow cover in an area is available as the depth of snow on the ground. The more completely the snow covers the earth's surface in an area, the higher the surface albedo should be. However, from figures 1 and 2 and table 4, it is noted that depth of ground snow greater than approximately 5 in. is not necessarily related to an increase of the surface albedo. A ratio of the surface albedo with snow cover to that without snow cover is computed by comparing

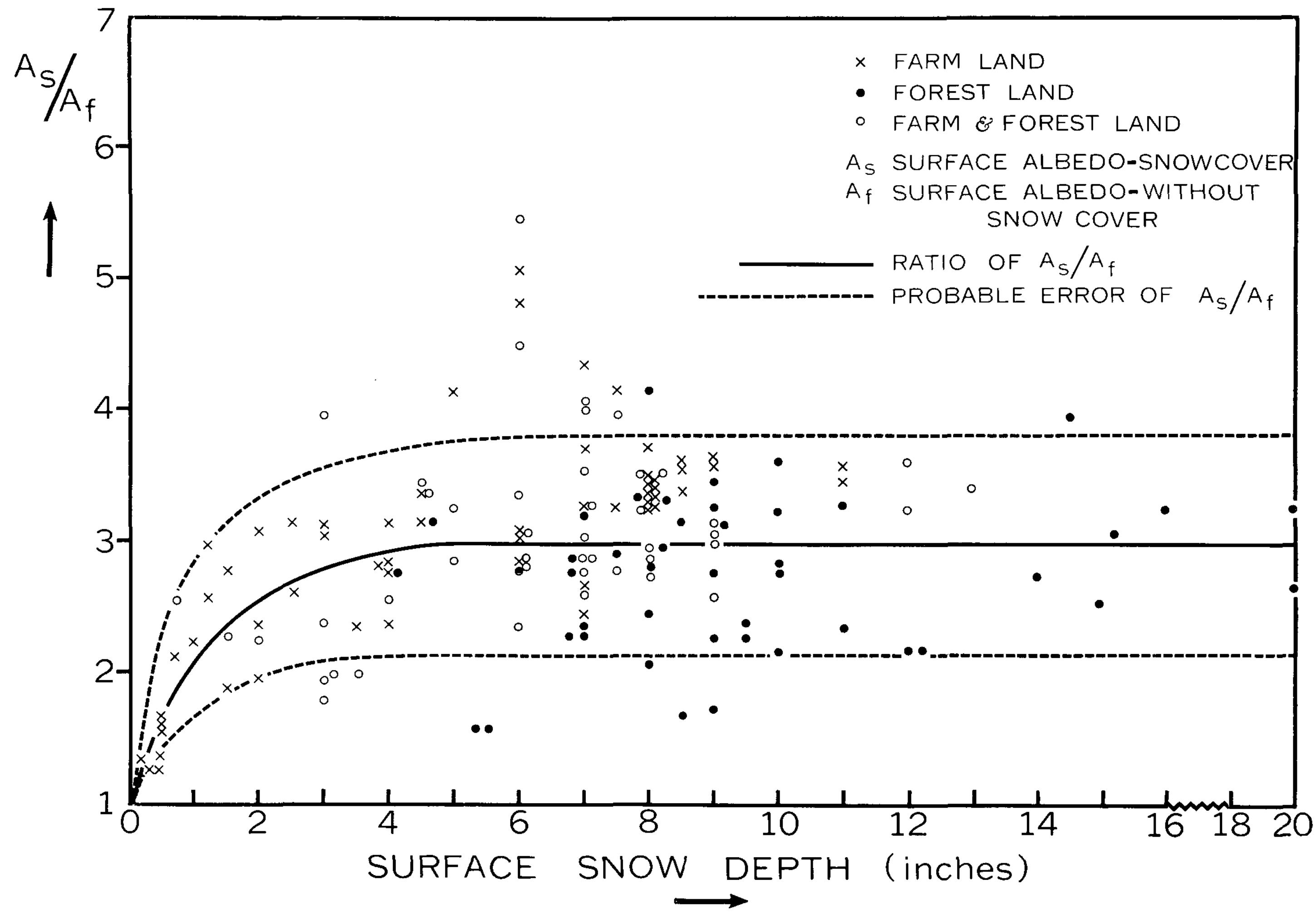

FIGURE 3.—Surface albedo related to depth of ground snow cover.

each month to April when the surface cover structure is most similar to that underlying the snow during the winter. This ratio was computed for each monthly surface albedo value of the sections during the snow-covered season along the Wisconsin flight path, and plotted against the ground snow depth of the area section as shown in figure 3, using different notations for farmland areas, forest areas, and mixed areas of farmland and forest.

The points in figure 3 are rather scattered. As a whole, the surface albedo increases rapidly as the snow accumulates, but after the snow accumulates 5 in. or so, there is no further increase in albedo. This can be explained as follows: exposed patches not covered by the snow decrease both in size and number as the snow depth increases, and after the snow accumulation reaches a certain depth, the forest trees and other bodies above the ground snow bear the maximum amount of snow cover on them that they can sustain. The ratio curve in figure 3 is about equal to 3 after the show depth reaches 5 in. and we can include most of the plotted values if we take arbitrarily $\pm$ 0.8 as the error range. It can be noted that generally the ratio in forests is comparatively low. This is understandable, since there are more dark bodies, such as stems, still exposed in the forest area than in farms, even after the tree canopy supports the maximum sustainable amount of snow. If the surface albedo does not increase significantly after the ground snow reaches a certain depth, then the scattered feature of the plotted values in figure 3 should be largely due to the reflectivity of the snow, which is affected by original crystal structure, freshness, etc.

7. ALBEDO OF VARIOUS TYPES OF SURFACE COVER OF THE NORTH AMERICAN CONTINENT

The albedo values observed during the long-range flights over North America over rather typical and simple surface covers are tabulated in table 6. These are listed separately for each flight mission because the flight dates may indicate the particular phenological state of the vegetation cover in the area. It must be kept in mind that the type of surface cover listed for an area in table 6 is not necessarily the only kind of surface cover in that area; it rather means that some kind of surface

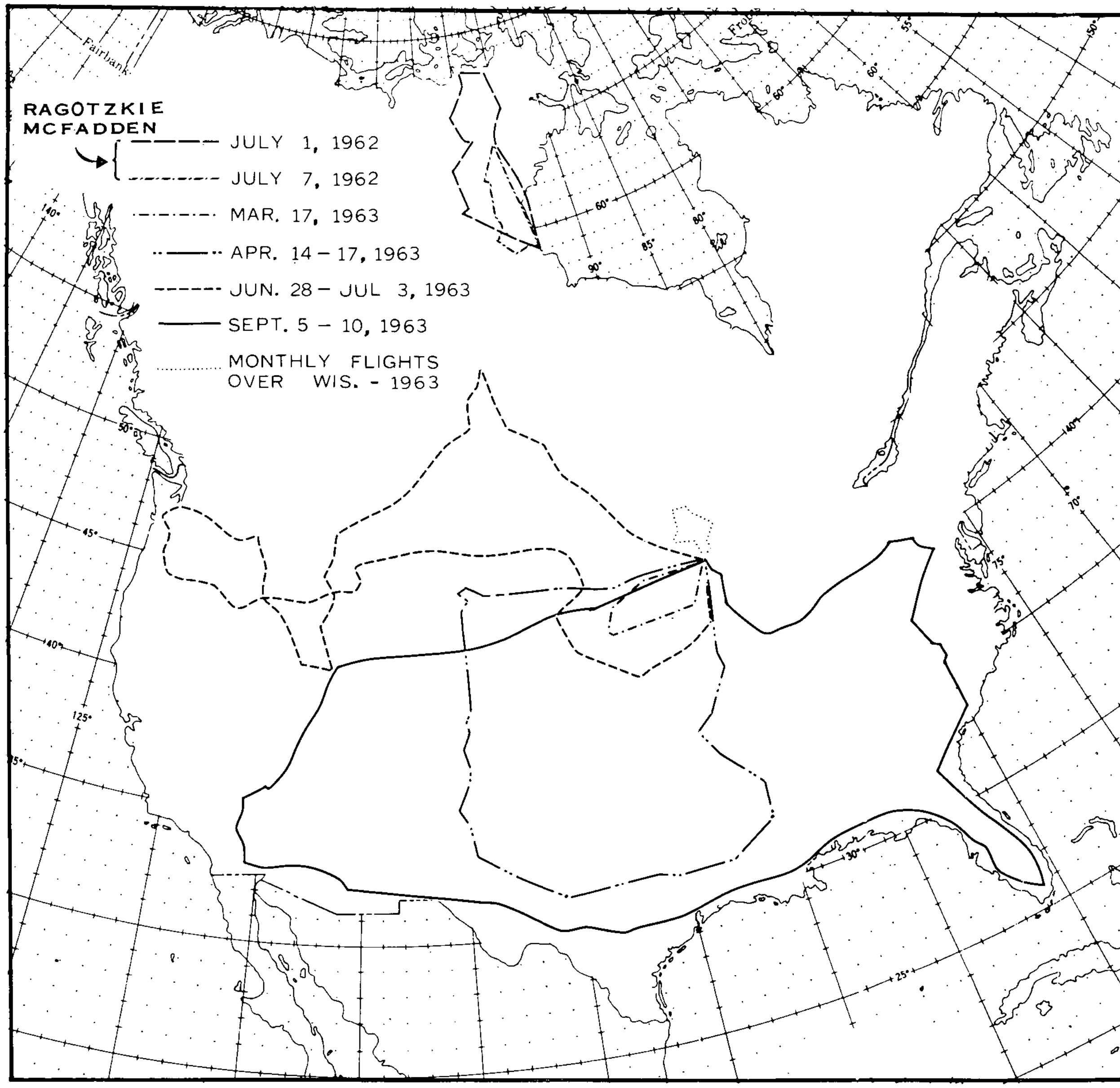

FIGURE 4.—Flight paths of continental surface albedo measurements over North America.

cover is heavily and uniformly dominant in such an area (see discussion in section 1).

Probably the only surface albedo measurement made on a continental basis before this study was Fritz's [14] observation on March 22, 1947, using the B–29 airplane from Washington, D.C., to Inyokern, Calif. The flight altitude varied from 2.1 to 5.3 km. and was usually 3 km.; thus, he was forced to extrapolate the measured value downward to the surface assuming the decrease of albedo with increase of pressure. Over the western mountains where less albedo extrapolation by height was involved, the agreement with our study seems good. Bauer and Dutton [1, 2] made regular flight investigations of the surface albedo over south central Wisconsin in 1959–60. Kuhn and Suomi [19] made several flight observations of the surface albedo during the summer of 1956 from O'Neill, Nebr., to Madison, Wis. Robinson [30] listed surface albedo values of various surface types over southern England as the results of his aircraft observations during 1954–57. The surface albedo values given by these previous investigators are comparable with our listing in table 6.

The Wisconsin monthly observation included the surface albedo of Madison; during other long-range flights, including the observation incidental to a Canadian eclipse observation on July 18–21, 1963, measurements were taken over other cities of various sizes. The observed values are listed in table 7 for those towns and their suburbs. As is seen in figure 1, and tables 3, 4 and 7, a city, as represented by Madison in the Wisconsin monthly flights, is the darkest area during the snow-covered season, except when the snow is not yet cleared or "darkened"

TABLE 6.—*Surface albedo over areas of typical surface cover in North America.* (*See fig. 4 for flight paths*)

Surface type	Locality	Surface Albedo	Surface type	Locality	Surface Albedo
		March 17, 1963			
Woody farm covered with snow	S.W. Wisconsin	33–40	Woody farm with old thin snow cover	S.W. Iowa	20–22
Corn field covered with snow	N.E. Iowa	50–51	Corn field	S. Iowa	14
Black plowed corn field	N.W. Iowa	9–11	Corn field along Mississippi	S.E. Iowa and N.W. Illinois	12–13
		April 14–17, 1963			
Woody farm with corn stubbles	N. Iowa	16–17	Deciduous forest	E. Texas	17
Pasture land and farmland mixed	N. Iowa	15–16	Pine forest	E. Texas	14
Plowed field	N.W. Iowa	15	Swamp and lagoon	N.E. Louisiana	14
Grassland, mostly pastured	W. South Dakota	17–19	Bare field	N. Mississippi	16–17
Dry farming field	E. Wyoming	20–22	Woody bare field	N. Arkansas	15–16
Dry grassland	S.E. Wyoming	21	Oak and hickory forest	S.E. Missouri	16–17
Pastured grassland	W. Colorado	19–20	Bare and green field mixed	Central Illinois	16–17
Desert shrubland	W. New Mexico	19–25	Farmland	N. Illinois, S. Wisconsin	16–17
Grassland, mostly pastured	Central Texas	17–18			
		June 28–July 3, 1963			
Woody farm	W. Wisconsin	15–16	Great Salt Lake (water)	N. Utah	3
Woody grassland	N.E. Minnesota	16–17	Shore of Great Salt Lake (salt)	N. Utah	25
Prairie	S.E. Manitoba	12–13	Irrigated farmland	S. Idaho	17
Swamp and field	S. Manitoba	12–13	Desert shrubland	S.W. Idaho	17
Woody farm	E. Saskatchewan	14	Meadow	W. Idaho	11–12
Farmland	S. Saskatchewan	15	Forest and bare soil	W. Idaho, S.E. Washington	11–12
Grazing land	N. and S. Montana	15–16	Glacier	Central Washington	27
Dry run ravine	N. Montana	17–18	Forest	W. Washington	14–16
Top of mountain (9,000 ft. high)	S. Montana	18	Dry farms	S. South Dakota	13–14
Bottom of valley (9,600 ft. high)	S. Montana	14–15	Farm and pasture land	W. Nebraska	15–16
Irrigated farmland	E. Idaho	15–16	Farmland	S.E. Nebraska, N.E. Kansas.	14–16
Black volcanic ash	S.E. Idaho	9			
Sagebrush hill	S.E. Idaho	14	Farmland	N. Missouri, W. Illinois	16–18
Salt flat	N. Utah	17–19			
		September 5–10 1963			
Farmland	W. Nebraska	16–17	Swamp	E. Texas, S.W. Louisiana	13–14
Irrigated farmland	W. Nebraska	17–18	Swamp forest	S.W. Louisiana	16–17
Dry grazing land	W. Nebraska, S.E. Wyoming.	19–22	Sugarcane field	S. Louisiana	16
			Swamp forest	S.E. Louisiana, S.W. Alabama, N.E. Florida.	11–12
Desert (brown sand)	W. Central Utah	23			
Lava flow	W. Central Utah	25	Citrus grove	W. Florida	16
Salty land	W. Central Utah	24	Swamp	S.W. Florida	10
Desert with salt-loving shrubs	W. Central Utah	29	Bare field	S.E. Florida	14–15
Desert shrubland (brown sand)	S.W. Utah	21	Forest	N.E. Florida, S.E. Georgia	13
Desert shrubland	S.E. Nevada	21–23	Ocean	S. South Carolina	5
Desert near Las Vegas	S.E. Nevada	24–27	Tidal flat	S. South Carolina	5–7
Irrigated field	S.E. California	18–23	Woody farmland	South Carolina, North Carolina.	14–15
Desert near Yuma	S.E. California	27–28			
Irrigated field	S.W. Arizona	20–23	Forest	Central North Carolina	14
Bare and green field near Casa Grande	S. Arizona	22	Woody farmland	S. Virginia	14–15
Sonora Desert	S. Arizona	22	Forested hill	S.W. Pennsylvania	14
Valley area	S.W. New Mexico	16–18	Farmland	Central Ohio	14–15
Irrigated field	W. Texas	19	Farmland	Indiana	14–16
Grassland	S. Central Texas	18			

as in the case of the Madison albedo value of December 19. This should be a significant factor in discussing the regional climate of the winter season. In table 7 a wide range exists in the albedo value for various cities. It is also obvious that there exists a difference between city and suburb albedo values in most of these cities. This difference can become an important factor when combined with other urban characteristics such as changes in the wind, moisture, etc., in a study of the city climate.

It is difficult to discuss the seasonal variation of the city albedo from our data. However it may be conceived that the city albedo can be strongly affected by the temporal factors of locality.

8. CONTINENTAL SURFACE ALBEDO MAPS

Surface albedo maps are a preferable way to illustrate the horizontal and seasonal variations of the surface albedo over a continent. The constructed maps can also

TABLE 7.—*Surface albedo of town and suburb in various cities*

City	Date (1963)	Surface albedo	
		Town	Suburb
Madison, Wis	Feb. 21	15.4	17.9
Madison, Wis	Mar. 21	15.2	12.9
Madison, Wis	Apr. 11	16.3	14.7
Madison, Wis	June 12	14.9	15.0
Madison, Wis	Sept. 26	15.9	14.2
Madison, Wis	Nov. 19	17.8	13.9
Madison, Wis	Dec. 19	41.3	37.8
Ogden, Utah	June 30	15.6	16.6 (salt flat)
Boise, Mont	July 1	17.0	18.7 (irrigated field)
Wausau, Wis	July 18	13.1	15.5
Duluth, Minn	July 18	12.4	16.2
Winnipeg, Manitoba	July 18	15.9	13.0
Grand Forks, N. Dak	July 21	14.0	15.9
Las Vegas, Nev	Sept. 6	19.5	26.5 (desert)
Yuma, Ariz	Sept. 6	20.0	19.4
Gila Bend, Ariz	Sept. 6	22.9	23.5
Tucson, Ariz	Sept. 6	22.0	20.4
San Antonio, Tex	Sept. 7	18.1	16.7
Houston, Tex	Sept. 7	-------	16.6
Port Arthur, Tex	Sept. 7	16.5	15.7
Mobile, Ala	Sept. 8	14.0	13.1
Miami, Fla	Sept. 9	17.7	14.1
Jacksonville, Fla	Sept. 9	-------	15.1
Waycross, Ga	Sept. 9	15.2	11.4
Jessup, Ga	Sept. 9	14.5	11.6
Washington, D.C	Sept. 10	12.5	13.1
Zanesville, Ohio	Sept. 10	12.1	15.1
Columbus, Ohio	Sept. 10	13.7	16.1
Cincinnati, Ohio	Sept. 10	13.0	15.3
Bloomington, Ind	Sept. 10	16.8	14.7
Champaign-Urbana, Ill	Sept. 10	16.6	16.0

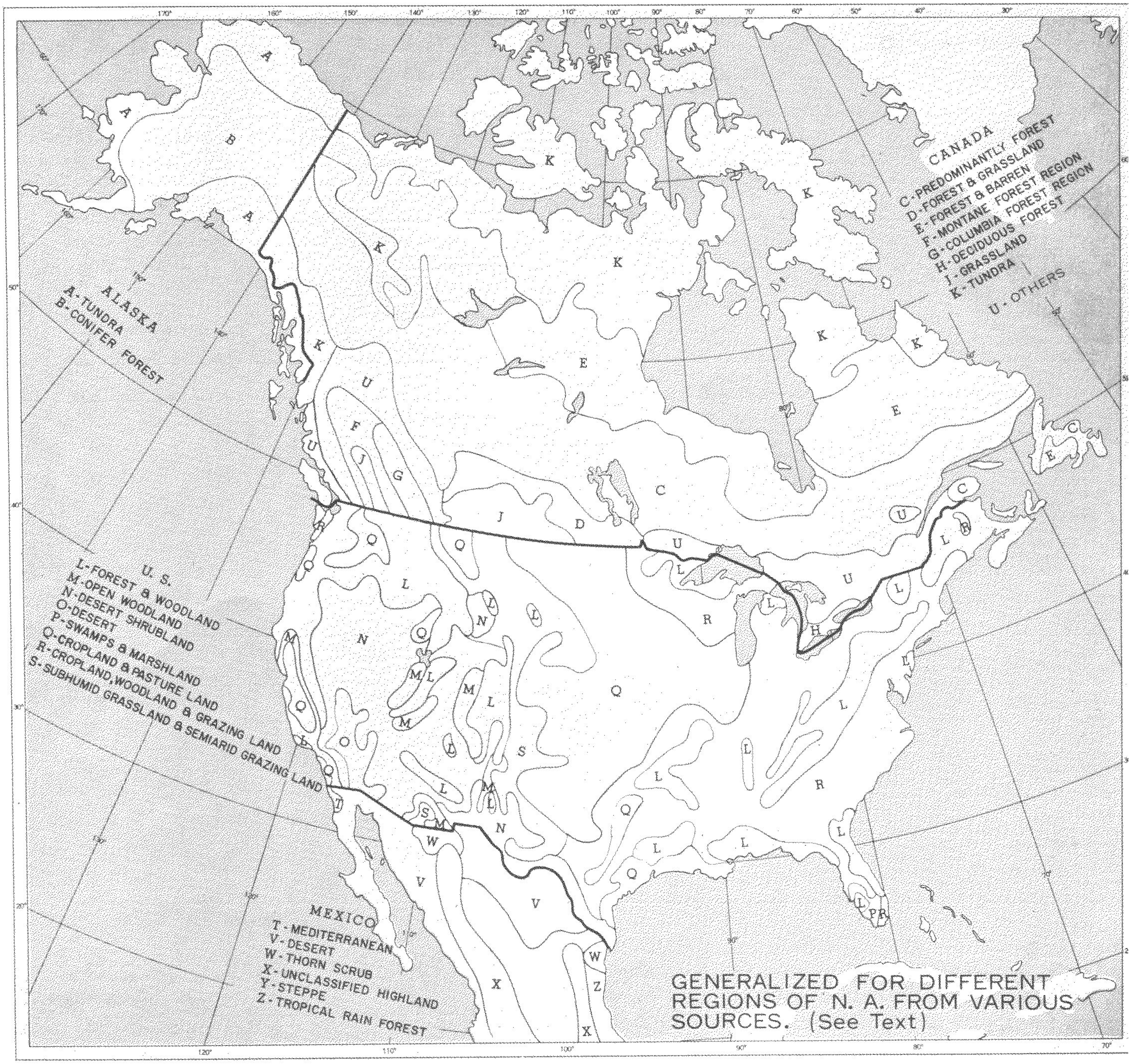

FIGURE 5.—Generalized pattern of land use and forest cover for North America.

be used in the study of atmospheric behavior. The results of the Wisconsin monthly flights and other long range flights over North America, as presented in the foregoing discussions, show characteristic surface albedo values for surfaces of different structure. Since the regional surface albedo is a combined reflectivity of the materials composing the earth's surface cover, areas of the same or almost the same surface texture are expected to have the same or almost the same surface albedo value.

The texture of the surface cover over the North American Continent was studied mainly in terms of land use, vegetation type, phenology of vegetation, soil types, snow cover of the ground, etc. Generalized patterns of land uses and forest types, which are the basic structures of the continental surface cover, are outlined in figure 5 from various sources (Marschner [21]; U.S. Department of Agriculture [39]; Rowe [31]; Raisz [28]; world atlases [10], [16]; and others). However, the patterns shown on figure 5 are immensely simplified; to study the similarities and differences in surface texture among the regions, more detailed information on land use and vegetation type was examined along with the knowledge of phenol-

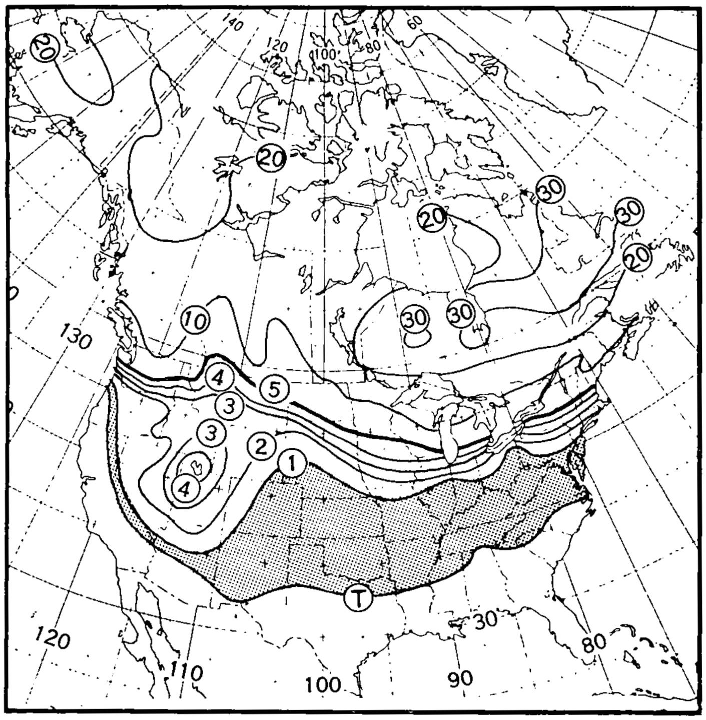

FIGURE 6.—Multi-annual average depth of snow cover, in inches, for January 31 over North America as adapted and interpolated from the U.S. Army Corps of Engineers [36].

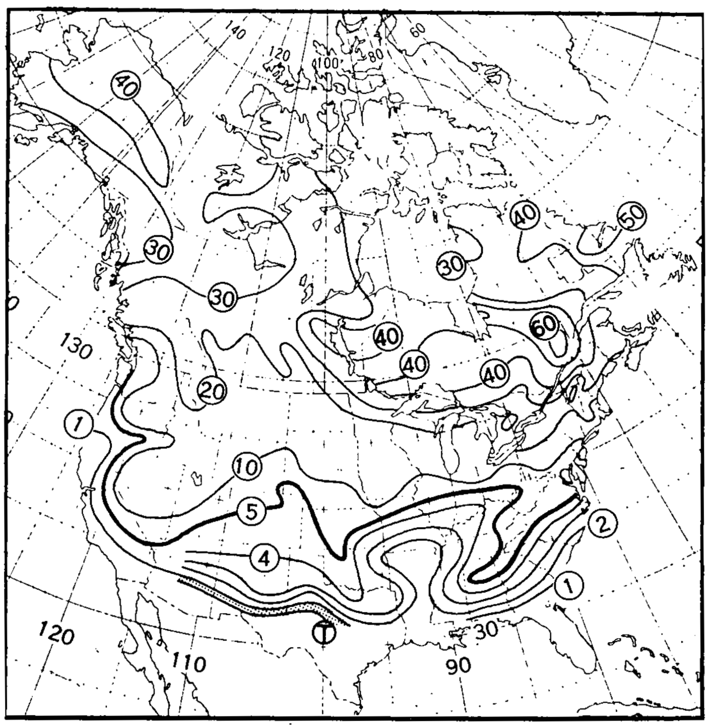

FIGURE 7.—Multi-annual maximum depth of snow cover, in inches, for January 31 over North America as adapted and interpolated from [36].

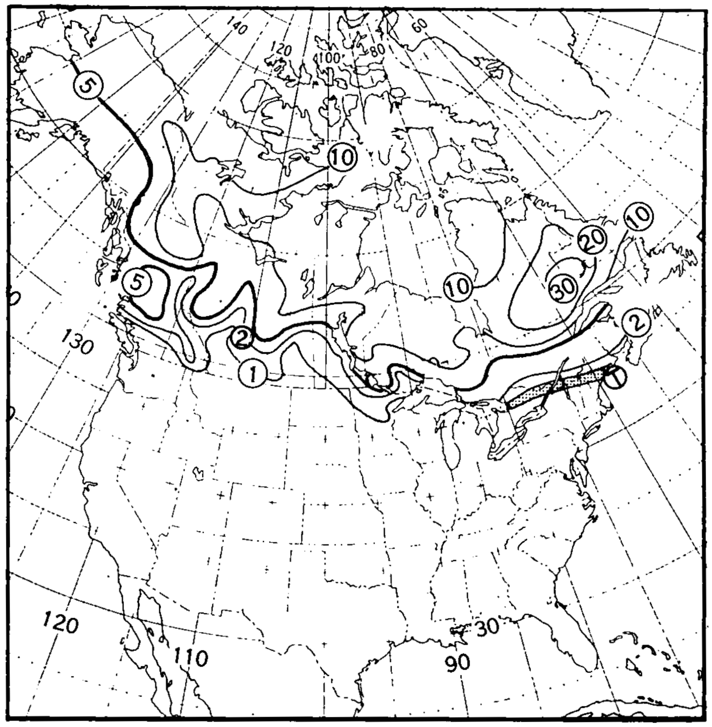

FIGURE 8.—Multi-annual minimum depth of snow cover, in inches, for January 31 over North America as adapted and interpolated from [36].

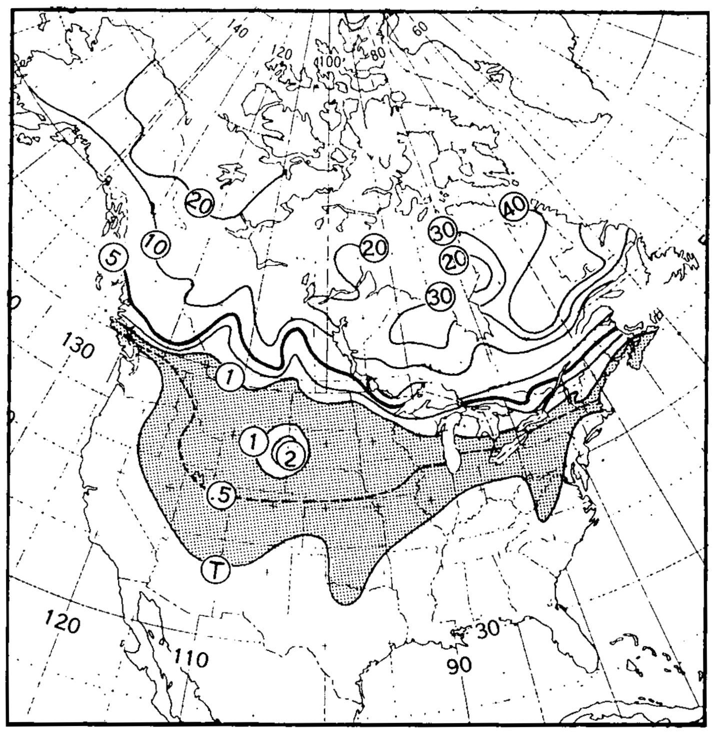

FIGURE 9.—Multi-annual average depth of snow cover, in inches, for March 31 over North America as adapted and interpolated from [36].

ogy, soil types, and others. For these, reference was made to Curtis [7], Cunningham, Horn, and Quinney [6], Dominion Bureau of Statistics [8], Ferguson and Longwood [11], Ferguson and McGuire [12], Findell and Pfeifer [13], Hole and Beatty [17], Hutchinson and Winters [18], Nebraska Conservation Needs Committee [22], New Jersey Department of Agriculture [23], Marschner [21], Pennsylvania Forest Industries Committee [24], Rowe [31], Salas [32], Stone and Thorne [35], Stone and Bagley [34], U.S. Department of Agriculture [37, 39], U.S. Departments of Agriculture and Commerce [38], Warner and Chase [42], West Virginia Conservation Needs Committee [41], Wisconsin Conservation Department [43], Wisconsin State Department of Public Instruction et al. [45], and correspondence was carried on with many other local conservation authorities. Multi-annual statistics of depth of the ground snow were adapted and interpolated from a publication of the U.S. Army Corps of Engineers [36], and are shown in figures 6 through 9.

On the basis of the above-mentioned information on the earth's surface cover over North America, surface albedo values can be assigned to various regions of the continent for each season using the surface albedo data measured by our flight observations.

In addition to our flight measurements, a few references were made to the albedo data obtained by other investigators. Albedo data obtained by Ragotzkie and McFadden [27] during flights in northern Canada on July 1 and 7, 1963, (see fig. 4 for flight path) were referred to in mapping albedo of this area. Ragotzkie and McFadden's [26] flight albedo observations during the period October 24 to November 10, 1961 over Manitoba, western Ontario, Minnesota, and Wisconsin gave additional information concerning the albedo of some boreal snow-covered surfaces. Albedo of various stages of lake ice were adopted from observations by Bauer and Dutton [1, 2] over Lake Wisconsin and Lake Mendota. These references were employed because their instrumentation systems resembled ours and also their albedo data could be checked against our data.

Since our albedo measurements of the snow-covered earth's surface were typically taken two or three days after a major snowfall, the consequent snow-covered albedo values in the constructed maps should represent those values with "moderately fresh" snow. According to the discussion in section 6, it was assumed that an accumulation of ground snow more than 5 in. does not contribute to an increase in the albedo value. When direct observational information of the snow-covered surface albedo was not available for regions of particular surface structures, the albedo values were interpolated, using the relationship between surface albedo and snow cover as discussed in section 6.

The major annual cycle of the surface albedo variation, the snow-covered season and the snow-free season, suggests the construction of three types of seasonal surface albedo maps: a winter map, a summer map, and a map for seasons of transition. Where a phenological cycle of vegetation is apparent, there also exists a secondary, but statistically significant, variation during the snow-free season. This was considered in plotting the summer map and the snow-free part of the transitional season.

According to the method described above, seasonal surface albedo maps were constructed for North America as shown in figures 10 through 14. Figure 14 is the summer surface albedo map, which shows the basic pattern of the reflectivity of the earth's surface over North America when snow does not exist. The high albedo above 20 characterizes the desert areas in the western United States. The low albedo values are found mainly over areas of swamp, swamp forest, oak-hickory forest, and some pine forests. The characteristic regional variation of the surface albedo due to different textures of the surface cover is apparent in the summer map. Nevertheless, the differences among regions are not as striking as in maps of snow-covered seasons.

Figures 10, 11, and 12 show the winter surface albedo maps constructed by using three different snow-cover patterns in the midwinter. Figure 10 is the winter map constructed by using the multi-annual mean January 31 snow depth in figure 6. Figures 11 and 12 were constructed by using the multi-annual statistics of maximum January 31 snow depth in figure 7 and minimum January 31 snow depth in figure 8, respectively. Thus figure 10 displays the normalized situation of the surface albedo in the winter over the continent, while figures 11 and 12 respectively indicate the possible highest and lowest albedo patterns in the midwinter over the continent.

When and where the earth's surface is deeply snow-covered, high albedo values above 60 are found in the areas of frozen lakes, tundra, prairie, desert, and farms, while relatively low albedo values are found in the forested areas depending on the density and types of the forest. When the ground snow depth is shallow (i.e., less than 5 in.), the variable intermediate albedo values between deeply snow-covered and snow-free values are observed. The patterns presented in figures 10 and 11 are quite different from that of the summer map and the differences of albedo values among regions are very large. Figure 12, the winter surface albedo map of possible minimum ground snow cover, is quite different from figures 10 and 11. Since the earth's surface can be essentially free of snow in the United States in the midwinter as shown in figure 8, the pattern resembles that of the summer map south of approximately 45°N., while the northern part of the continent shows the snow-covered albedo values.

The surface albedo map of the transitional seasons between winter and summer is shown in figure 13. This map was constructed with the multi-annual mean March 31 snow depth of figure 9. As the ground snow becomes much less than that of the average winter condition in the United States and southern Canada, the gradual decrease of the albedo value from north to south corresponding to that of snow depth is the characteristic of

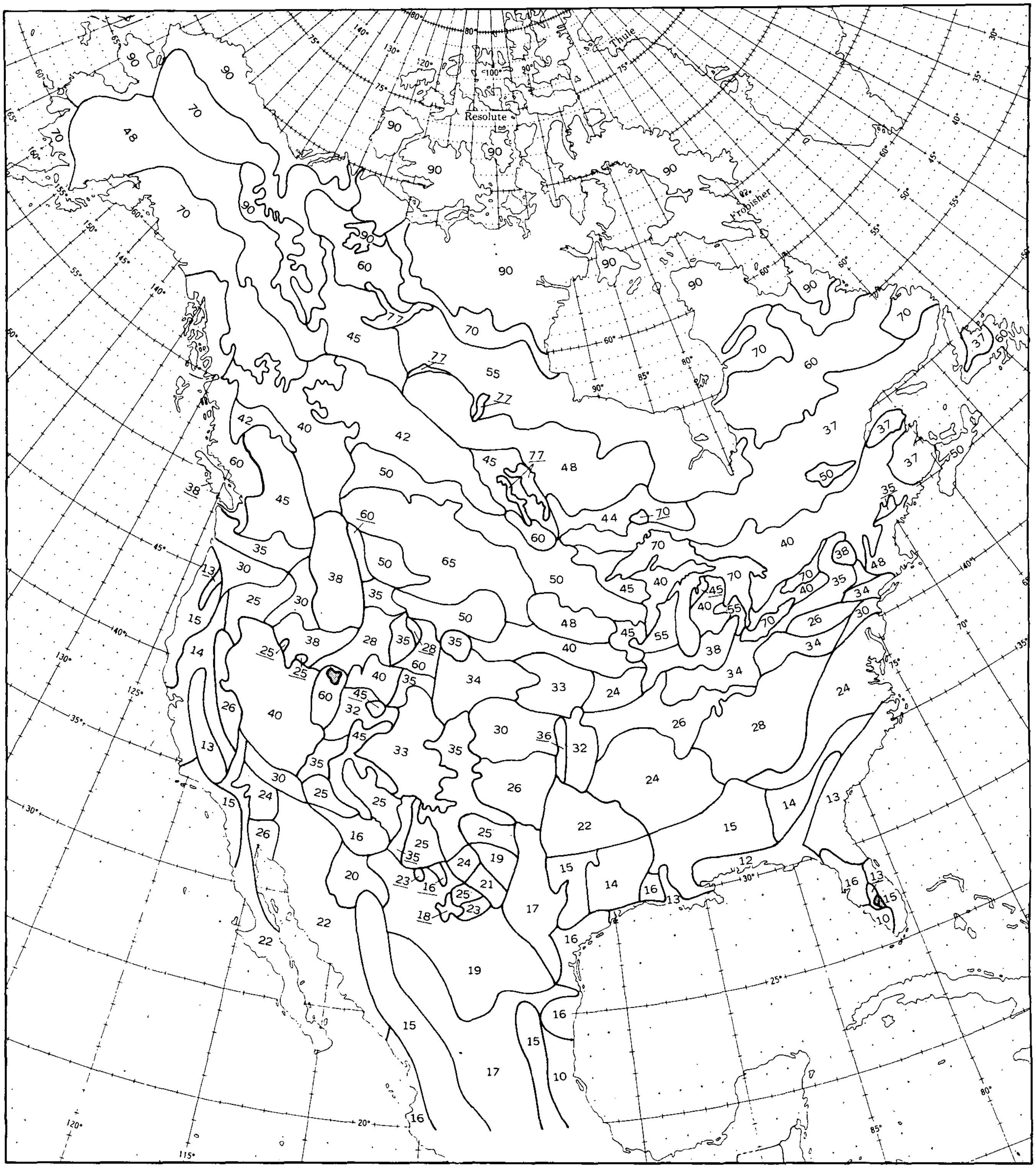

FIGURE 10.—Winter surface albedo map for North America (using mean January 31 snow cover).

this map. The differences of the snow-free albedo values for different seasons in a single region, as observed in figures 10 through 14, reflect the phenology of the vegetation cover.

The constructed albedo maps, especially the summer map, show more complicated patterns over the middle latitudes than over northern and southern parts of the continent, for two reasons. First, the earth's surface characteristics are complex over the United States, except Alaska; second, the information on land uses is more restricted for Alaska, northern Canada, and Mexico than for the United States.

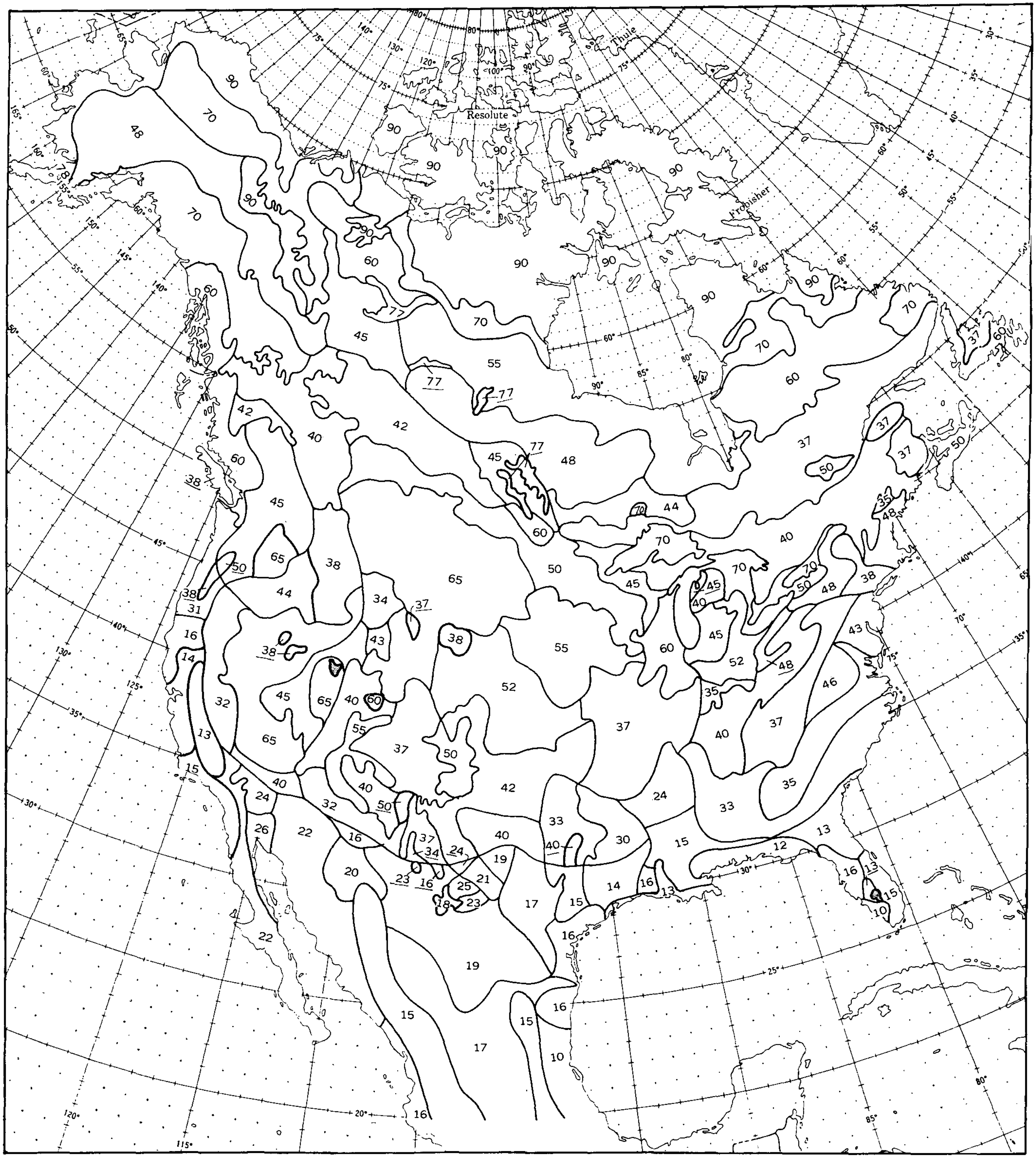

FIGURE 11.—Winter surface albedo map for North America (using maximum January 31 snow cover).

Before this study an approximation of the global surface albedo maps was made by Posey and Clapp [25] using previously existing albedo data. The general trends on their maps are comparable to those shown here.

It is interesting to examine the constructed surface albedo maps from the large-scale point of view. From the maps presented in figures 10 through 14, the zonal and continental means of the albedo may be estimated for each seasonal map. The zonal mean for each 5° latitudinal band and the continental mean value were computed from 20° to 70°N. of the North American Continent using the area of the region as the weighting factor. The results are listed in table 8, and the meridional profiles of the continental surface albedo are presented in figure 15.

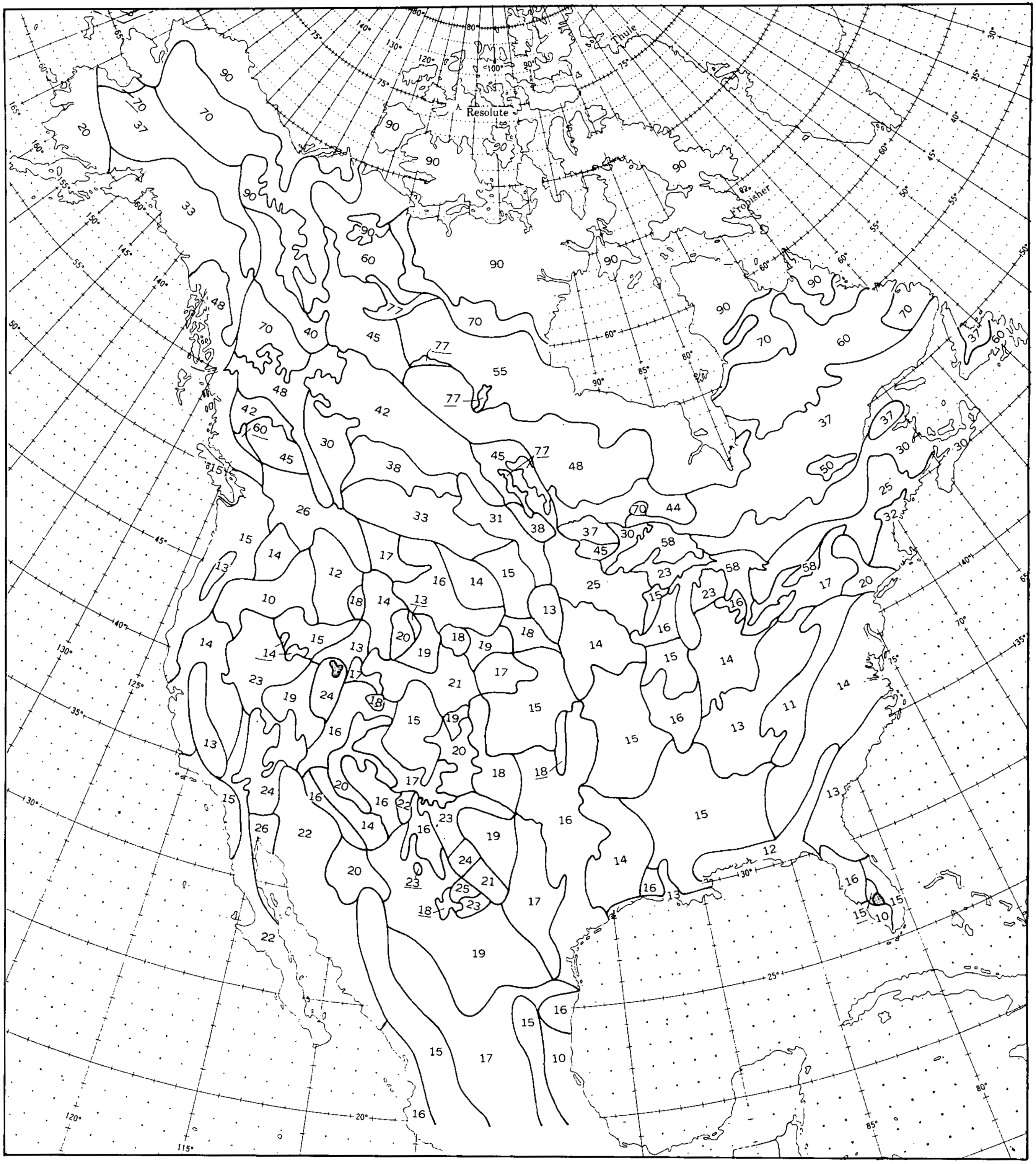

FIGURE 12.—Winter surface albedo map for North America (using minimum January 31 snow cover).

In the summer the north-south variation of the continental surface albedo is almost negligible in comparison with that of the snow-covered seasons. In the snow-covered seasons, the north-south difference of the surface albedo may be as large as 67 in contrast with at most 3 of the summer. The meridional profiles of the continental albedo during the snow-covered seasons show a very rapid increase from south to north. The seasonal variation of the continental albedo is negligible south of 30°N. on account of a lack of snow cover.

The effect of the presence and depth of the snow cover is most remarkable in the middle latitudes. In the 45°–40°N. latitudinal zone the albedo difference between winters of maximum and minimum snow depth may be as

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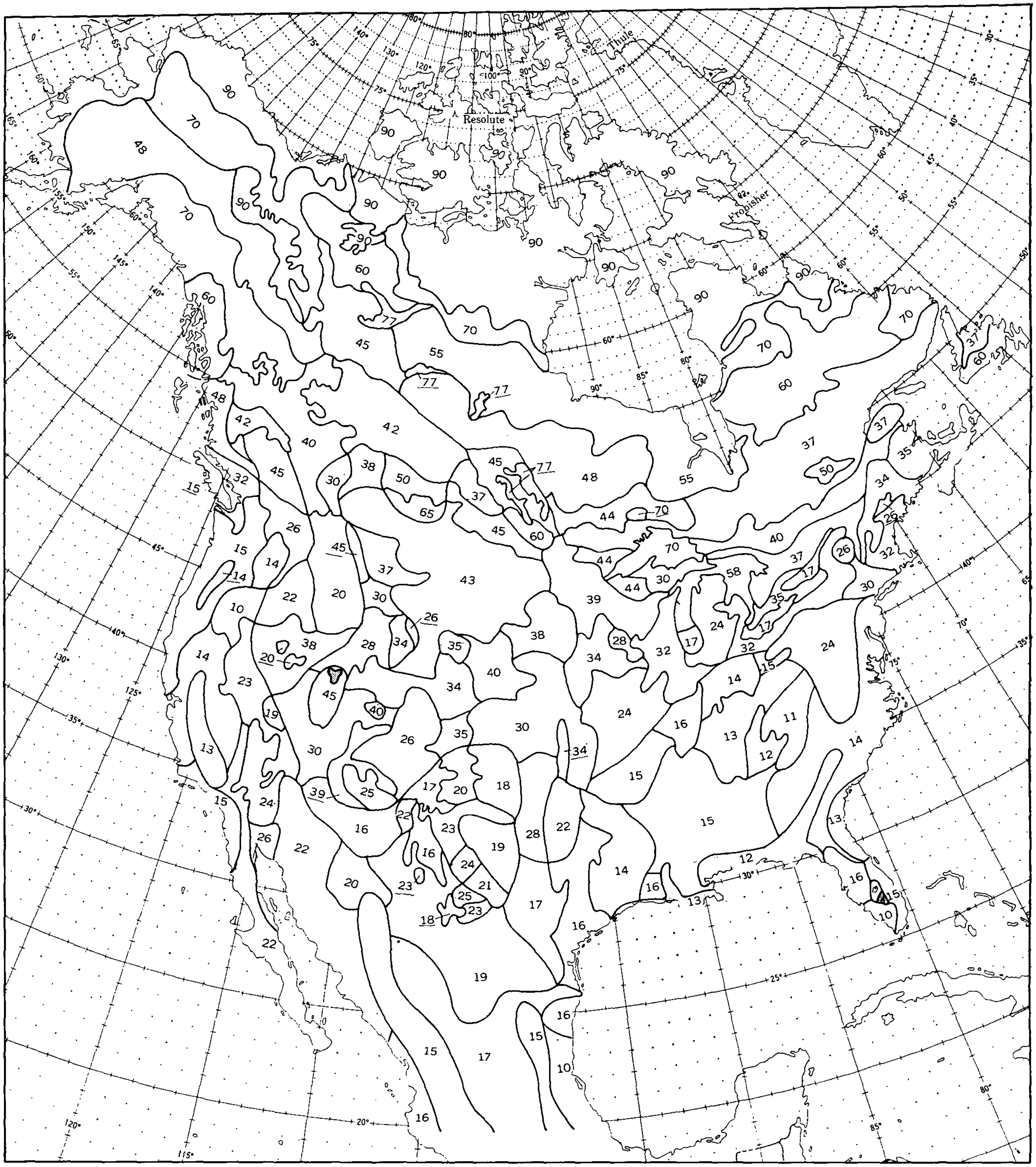

FIGURE 13.—Surface albedo map of transitional seasons between winter and summer for North America (using mean March 31 snow cover).

large as 31. In the middle latitudes, the existence of large fluctuations in the meridional profile of the surface albedo during the snow-covered season should be a significant factor in the study of the large-scale circulation. As an example, Lorenz [20] discussed a possible mechanism for irregular fluctuations in the intensity of the general circulation in relation to time variation of the albedo.

We designated figure 13, constructed with mean March 31 snow depth, as the albedo map of the transitional seasons between winter and summer. As shown in figure 13, the "transitional" feature of the albedo is most apparent in the middle latitudes around 40°N. It must be noted that the designated albedo pattern of the transitional seasons, as shown in figures 13 and 15, only

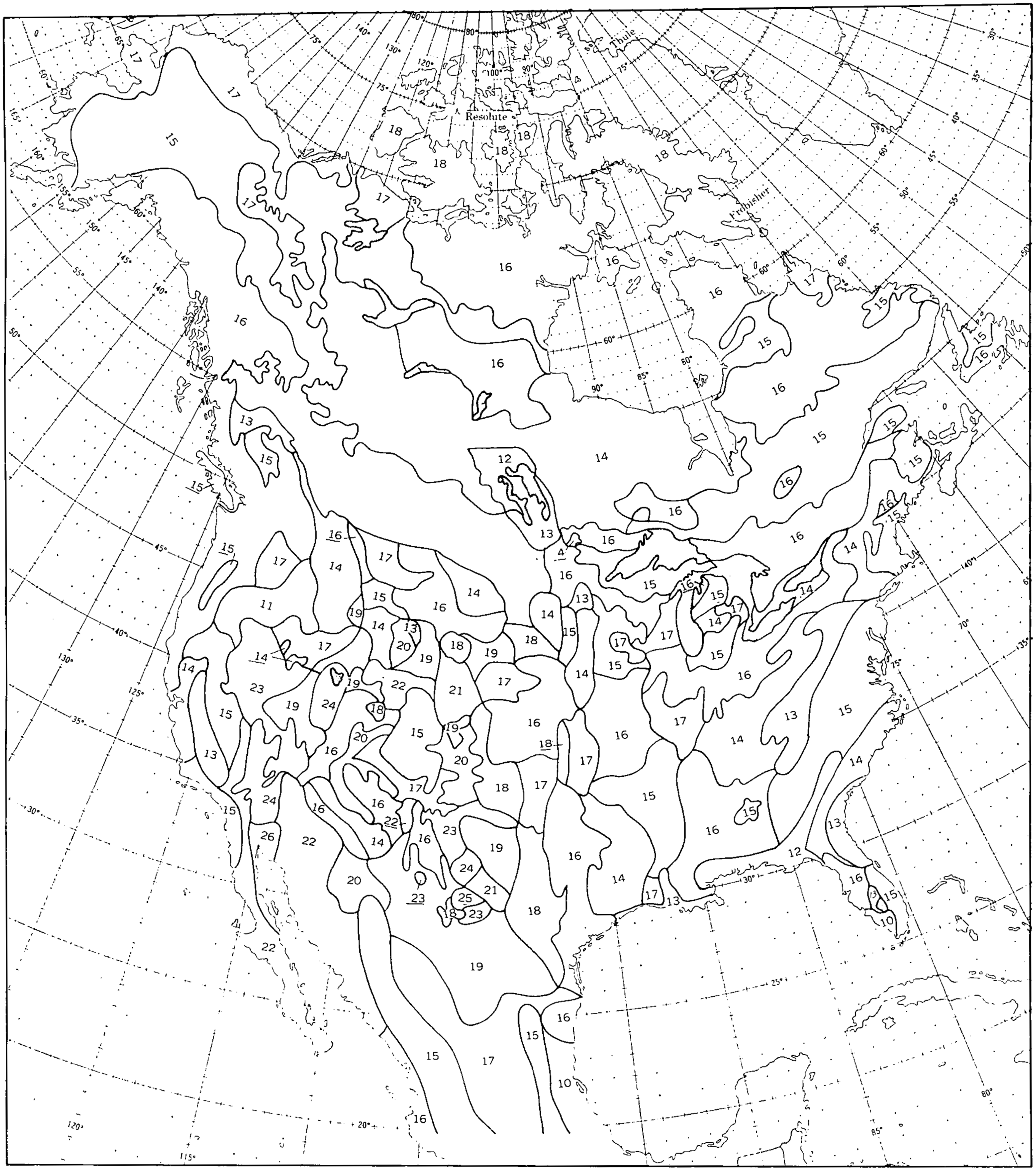

FIGURE 14.—Summer surface albedo map for North America.

implies the albedo of the transitional seasons, but it does not necessarily represent the gradual time variation of the seasonal albedo. As illustrated in figure 15, the average meridional albedo profile of the transitional seasons is well in the fluctuation range of the winter albedo, and resembles that of the average winter. Actually the decrease and increase of the surface albedo value in the transitional seasons are of a sudden nature in accordance with snow melting and falling, as observed in the Wisconsin monthly flights (see fig. 1). This is an important feature in discussions of air mass modification in relation to the march of seasons (see Bryson and Lahey [4]). In the 45°–40°N. latitudinal zone, for instance, the zonal albedo drops immediately to half of the shallow snow-covered early spring value of 31 after the snow melts.

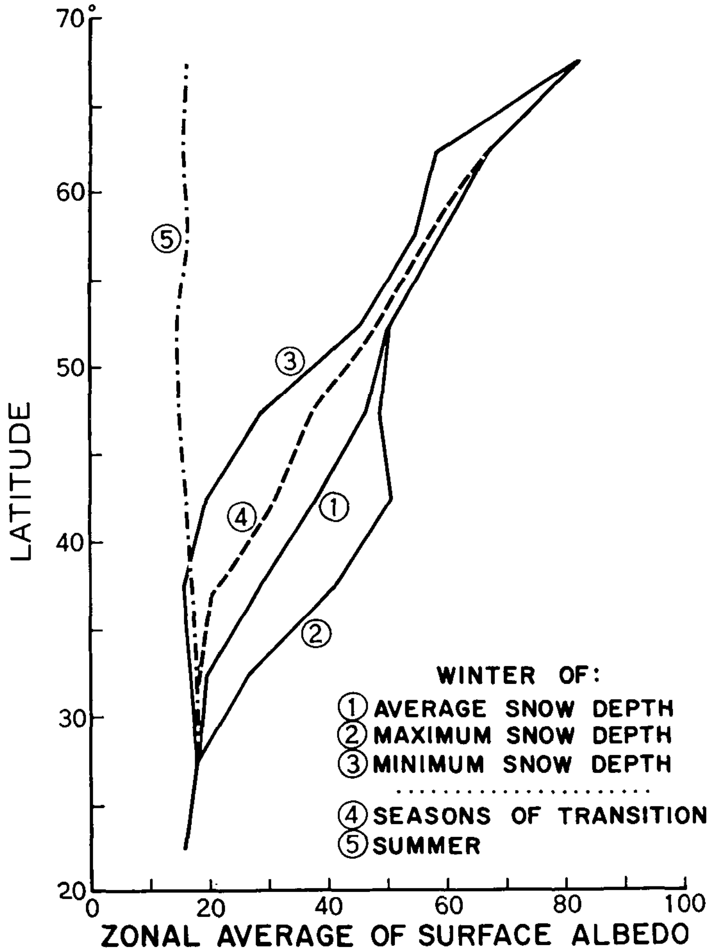

FIGURE 15.—Seasonal variation of meridional profile of continental surface albedo over North America.

The seasonal change of the surface albedo is also apparent in the continental mean (table 8). The mean of the summer albedo over North America is 16. The mean for the average midwinter is 43, and the spring or late fall value as designated by the transitional seasons is 39. The midwinter value may fluctuate between 35 and 47, depending on the snow cover.

9. CONCLUDING SUMMARY

To study systematically the basic features of the surface albedo variation in relation to the type of surface cover and the march of seasons, a series of 12 monthly flights along a selected flight path in Wisconsin and a series of four long-range flights over extensive areas of the United States and Canada were performed with a light, twin-engined airplane, which was equipped with an upward-facing Kipp and Zonen hemispherical solarimeter and a downward-facing parabolic reflector with a Kipp and Zonen solarimeter at the focus. Roughly 210,000 sets of the measurements taken during the approximate total flights of 24,000 mi. were processed for analysis.

TABLE 8.—*Zonal and continental means of surface albedo over North America*

Latitudinal zone (° N.)	Continental Surface Albedo				
	Winter of mean snow depth	Winter of max. snow depth	Winter of min. snow depth	Transitional seasons	Summer
70–65	82.8	82.8	82.7	82.8	16.1
65–60	67.3	67.3	58.2	67.3	15.6
60–55	59.1	59.1	54.8	57.7	16.5
55–50	50.3	50.3	45.8	48.0	14.6
50–45	46.4	48.9	28.4	37.6	14.8
45–40	37.9	50.4	19.0	30.5	15.8
40–35	28.5	40.8	16.0	21.1	16.5
35–30	19.1	26.2	16.9	17.4	17.2
30–25	17.8	17.8	17.8	17.9	17.9
25–20	15.8	15.8	15.8	15.8	15.8
Continental Mean	43.0	47.4	34.7	39.4	16.0

The observed surface albedo values, with the aid of the analysis of variance of the data, clearly indicate that there are statistically significant differences of albedo values among regions of different types of surface cover (uniform or variously intermingled surface covers), and that the march of seasons can be traced in the observed albedo values. An annual cycle of the regional surface albedo is recognized in Wisconsin; the very high value in the winter suddenly drops after snow melts in the spring, rises somewhat during the early and midsummer, falls again to its lowest value during the fall, and then rises back to the high winter value with the coming of the snow. Snow-covered and snow-free albedoes are the two major seasonal variations of the surface albedo. However, the variation of the surface albedo during the snow-free season also has a statistically significant nature, and it appears to reflect the phenological cycle of the vegetation.

The snow cover and the bodies (i.e., trees, buildings, etc.) not covered by the snow are two major factors determining the regional albedo values during winter months. When the ground snow is rather shallow and there are patches not snow-covered, the surface albedo is apparently related to the depth of snow, but further accumulation of the snow does not seem obviously to increase the albedo value after the ground snow depth reaches 5 in.

The coefficient of variability of the surface albedo (i.e., percent ratio of the standard deviation to mean in a section of the flight paths) expresses complex variability in the surface cover within the section.

Over the North American Continent, the surface covers and their texture were studied mainly in terms of land use, vegetation type and phenology, soil type, and ground snow cover. The surface albedo values were estimated for various regions of the continent from the extensive flight measurement data and the results of the data analysis, considering the similarity and differences in surface structure among the regions. Land uses and forest types are the most basic structures of the continental surface cover, and the snow depth is the most important modification of the earth's surface in evaluation of the regional surface albedo. In consequence of the albedo evaluation, seasonal surface albedo maps were constructed over North America for winter, summer, and seasons of transition. Three winter albedo maps are composed in accordance with the average and possible maximum and minimum snow depths over the continent. In turn these three winter albedo maps should indicate the normalized and possible highest and lowest surface albedo patterns in the midwinter.

Examination of the meridional profile of the continental surface albedo over North America shows that the winter surface albedo increases rapidly from south to north, but this north-south variation of the albedo is almost negligible in the summer. There exists a remarkable fluctuation in the continental albedo profile, especially in the middle latitudes, due to the presence and depth of the snow cover.

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